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Carbon pay back period for solar and wind energy project installed in India: A critical review

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ABSTRACT

All renewable energy systems make some contribution to climate change. This is due to fuel combusted for their construction and as back up energy during their operation. Accurate calculation of greenhouse gas emission per kilowatt hour of electricity is difficult but is an important part of policy making and planning. This study, an attempt has been made to analyze and review the development and potential of wind and solar energy in India. LCA has been carried out for the on shore wind turbine and poly crystalline PV module. Based on the past studies, life cycle inventory data has been collected for the investigation. Using that data, the detailed investigation has been made for the existing grid connected 1.65 MW wind turbine project in and around Udumalpet, Tamil Nadu and 25 kW Roof top solar PV Power plant at Sewa Bhawan, New Delhi. Carbon intensity, energy pay back period and carbon pay back period for the above system have been calculated and compared with each other.

Contents

Abbreviations: GHG, Greenhouse gases; IPCC, International Panel on Climate Change; LCA, Life cycle assessment; CIGS, Copper Indium Gallium Diselenide; PV, Numerical environmental total standard; CEA, Central Electricity Authority; MNRE, Ministry of New Renewable Energy; SPV, Solar photovoltaic; PCA, Process chain analysis; I/O, Input/Output; LCI, Life cycle inventory; BOS, Balance of system; EPBP, Energy pay back period; CPBP, Carbon pay back period; DC, Direct current; AC, Alternating current; CDM, Clean Development Mechanism; TERI, Tata Energy and Research Institute; IMD, Indian Meteorological Department

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1. Introduction

In the last few centuries the concentration of GHG (greenhouse gases) is rising in the anthropogenic origin in the atmosphere. According to the IPCC (International Panel on Climate Change) report, concentration of GHG is increasing in the atmosphere (for CO_2 by 29%, CH_4 by 150% and N_2O by 15%) in the last 100 years. They mean that the surface temperature has been arisen by 0.4–0.5 °C globally. The sea level also has risen at an average annual rate of 1–2 mm during this period. Industrial development is mainly contributing in the GHG emission. In India, Power sector is contributing 65% of the total CO_2 emission [1]. All electricity generation technologies generate carbon dioxide (CO_2) and other GHG emissions [2]. To compare the impact of these different technologies accurately, the total CO_2 amount emitted throughout a system's life must be calculated.

Emission can be both direct—arising during operation of the power plant, and Indirect—arising during other non-operational phase of life cycle. Performing an LCA is resource and time intensive. The accuracy of the final results depends upon the system boundaries and availability of data. Also, the reliability of LCA results depends strongly on the assumptions on lifetime, yield, thermal efficiency, fuel etc [3]. Conventional power production system uses coal, oil and natural gas as a fuel. The above components are rich in hydro carbon which emits more CO_2 and other GHG during combustion. Renewable energy power production system is emits very less carbon, compared with conventional power production. Among the various renewable energy technologies, solar and wind energy generation system are the emerging technologies and have vast potential in the world.

For wind turbines most of the GHG emissions arise at the turbine production and plant construction, which vary between 72 and 90% of cumulative emissions [4]. For instance, offshore wind turbines require significantly higher amounts of steel and cement than an on-shore counterpart for construction. GHG emissions are very low in the processes of operation & maintenance, decommissioning, transport of materials and turbine, which ranges between 10 and 28% of cumulative emissions [4]. The manufacturing process for both onshore and offshore wind plant is very similar, so life cycle assessment shows that there is little difference between the carbon foot print of onshore 4.64 gCO_2eq/kW h and offshore 5.25 gCO_2eq/kW h [2].

GHG emissions from the wind turbines are very site specific and sensitive to wind velocity conditions, because of the cubic relationship of wind velocity to power output. Since wind regimes vary significantly with geography that can be observed in the results, which lie between 8 and 30 gCO_2eq/kW he for onshore, and 9–19 gCO_2eq/kW he for off-shore turbines [5–11].

From various life-cycle studies made for PV systems, which range between 43 and 73 CO_2eq/kW he [4], typically four systems have been assessed: mono-crystalline, polycrystalline, amorphous and CIGS (copper indium gallium Diselenide). Of the four systems, mono-crystalline plants, on average, may emit the least GHGs ranging between 43 and 62 gCO_2eq/kW he [4]. The other PV systems may emit between 50 and 73 gCO_2eq/kW he over the whole GHG life-cycle. Variations in the results are due to a range of factors, such as the quantity and grade of silicon, module efficiency and lifetime, as well as the irradiation conditions. [4].

A 500 kWp solar power plant is in Thailand. Two types of solar cell for the power plant, multi crystalline silicon (m-Si) solar cell and thin film amorphous silicon (a-Si) solar cell, are considered [12].

LCA results of the solar cell power plant in Switzerland using the new eco-invent database found that important environmental impacts were not directly related to the energy use of the solar energy electricity generation but the impacts occurred at its module production [4] as the assessed results in the Netherlands [13] and the USA [14,15] also show. In Japan and Thailand, the numerical environmental total standard (NETS) method and the LCA technique has been applied to study the environmental impacts of the power plant systems.

In multi crystalline silicon (m-Si) solar cell power generation system, the largest impact was at the manufacturing process of the array field due to natural resource (i.e. silicon and aluminum) consumption [16]. The energy requirement of present day crystalline silicon modules vary considerably; between 2400 and 7600 MJ/m^2 for the multi crystalline (mc-Si) technology and between 5300 and 16,500 MJ/m2 for single-crystalline (sc-Si) technology [17–20]. Partly, these differences can be explained by different assumptions for process parameters like wafer thickness and wafering losses. Silicon purification process requires 900–1700 MJ/kg and Czochralsky process requires 500–2400 MJ/kg, primary crystalline step requires 2400 MJ/kg of energy [21].

The present work discusses about the strategies and development of wind energy and solar PV system in India. Life-cycle assessment has been carried out in existing power plant of some selected wind turbine and solar roof top PV system in India. In order to identify the environmental impacts, energy payback period, carbon intensity and carbon payback period has been calculated for the above system.

2. Power scenarios in India

The average electricity consumption in India is still among the lowest in the world at just 630 kW h per person per year, but this is expected to grow to 1000 kW h in the near future. According to Central Electricity Authority (CEA), the peak electricity demand in 2008 was 120 GW of power, while only 98 GW could be supplied. According to an analysis by the Indian PV project developer Aston field, this deficit is likely to grow to 25 GW by 2012. The Ministry of Power has set an agenda of providing "Power to All" by 2012.

India plans to bridge the peak deficit using a number of avenues. Many of them rely on increasing the fossil fuel footprint and hence indeed increase our reliance and dependence on these fossil fuels. At the same time, the government also making serious efforts to accumulate the growth of renewable contribution to power.

Some of the highlights of the current power production status in India had given in Tables 1 and 2. It is inferred that the total installed capacity of power plant in India as on December 2012 is 210,952 MW. The major source for power production is coal

based power plants. From Table 1 the private sector is contributing the major amount of power production in India [22]:

2.1. Potential of renewable energy

India's current electricity installed capacity is 210,952 MW. Currently there is peak power shortage of about 10% and overall power shortage of 7.5%. The 11th plan target is to add 100,000 MW by 2012 and Ministry of New Renewable Energy (MNRE) has set up target to add 14,500 MW by 2012 from new and renewable energy resources out of which 50 MW would be from solar energy. The Integrated Energy Policy of India envisages electricity generation installed capacity of 800,000 MW by 2030 and a substantial contribution would be from renewable energy [23].

Table 3 describing the renewable power potential and installed capacity in India. More than 25,197 MW power has been produced from various renewable energy sources. Among the systems, wind energy system contributes 70% of the total power production. India occupies fifth place in the world in wind energy generation after USA, Germany, Spain, and China. [24]. Wind power potential has been assessed assuming 1% of land availability for wind farms requiring at 12 ha/MW in sites having wind power density in excess of 200 W/m^2 at 50 m hub-height. Now India has started to use the solar energy with appropriate technology. India has very huge solar power potential.

Table 1
Installed capacity of power plant in sector wise.

S. no	Sector	MW	Contribution (%)
1	State sectors	86715.85	41.11
2	Central Sectors	62826.63	29.78
3	Private Sectors	61409.24	29.11
	Total	210951.7	100.00

Table 2
Installed capacity of power plant in fuel wise.

S. no	Fuel	MW	Contribution (%)
1	Coal	120873.4	57.30
2	Gas	18903.05	8.96
3	Oil	1199.75	0.57
4	Hydro	39339.4	18.65
5	Nuclear	4780	2.27
6	Renewable energy*	25856.14	12.26
	Total	210951.7	100.00

* SHP=Small hydro project, BG=Biomass gasifier, BP=Biomass power, U & I=Urban & Industrial waste power, RES=Renewable energy sources.

2.1.1. Wind energy

Wind has considerable amount of kinetic energy when blowing at high speed [25]. This kinetic energy when passing through the blades of the wind turbines is converted to mechanical energy and rotates the wind blades [26] and the connected generator, thereby producing electricity. A wind turbine primarily consists of main tower, blades, nacelle, hub, main shaft, gear box, bearing and housing, brake and generator [27]. The main tower is 50–100 m high. Generally, three blades made up of fiber reinforced polyester are mounted on the hub, while in the nacelle the major parts are housed. The hub connects the gearbox and the blades. Gear box is used to increase the speed ratio so that the rotor speed is increased to the rated generator speed [26]. It is most critical component and need regular maintenance. Oil cooling is employed to control the heating of the gearbox. Gearboxes are mounted over damper to minimize the vibration. Failure of gear box may put plant out of operation for an entire season as spares are often not available [28]. Thus, new gearless configurations have become attractive for wind plant operators.

Ten machines near Okha in the province of Gujarat were some of the first wind turbines installed in India. These 15-m wind turbines overlook the Arabian Sea [29]. Now, in 2012, there is an installed capacity of 17,253 MW; however, three times that potential, or 45,195 MW, exists are shown in Table 4 [30] stated below:

Table 4 describes about the state wise installed capacity of wind power plant for last 10 years in India. The leading installed capacity of wind plant is in Tamil Nadu (42%) [24,30].

The following factors are considered as the key performance indicators of the wind turbine. Power production depends up on the below factors [31].

1. Start-up speed—This is the speed at which the rotor and blade assembly begins to rotate.
2. Cut-in speed—Cut-in speed is the minimum wind speed at which the wind turbine will generate usable power. This wind speed is typically between 7 and 10 mph for most turbines.
3. Rated speed—The rated speed is the minimum wind speed at which the wind turbine will generate its designated rated power. Rated speed for most machines is in the range of 25 to 35 mph. At wind speeds between cut-in and rated, the power output from a wind turbine increases as the wind increases.

Table 3
Estimated power potential and achievements in India.

S. no	Source/systems	Estimated potential (MW)	Target for during 2012–2013 (MW)	Cumulative achievements as on 31.05.12 (MW)
Grid-interactive renewable power				
1	Biomass power (agroresidues and plantation)	16881	105	1176
2	Wind power	45195	2500	17534
3	Small hydropower (up to 25 MW)	15000	350	3406
4	Cogeneration-bagasse	5000	350	2012
5	Waste to energy	2700	20	90
6	Solar power	50 MW/sq.km	800	979
	Total		4125	25197
Off-grid/distributed renewable power (including capitive/CHP plants)				
7	Biomass power/cogen (nonbagasse)		60	388
8	Biomass gasifier		11.5	150
9	Waste to energy		20	104
10	Solar PV power plants and street lights		30	85
11	Aerogeneration/Hybrid Systems		0.5	2
12	Watermills/Microhydel		0.125	1877
	Total		126	729

Table 4
State wise installed capacity of wind power plant [24,30].

State	Up to March' 2005	2005–2006	2006–2007	2007–2008	2008–2009	2009–2010	2010–2011	2011–2012	Total
Andhra Pradesh	121.2	0.45	0.8	0	0	13.6	55.4	54.1	245.55
Gujarat	268	84.6	283.95	616.36	313.6	197.1	312.8	789.9	2866.31
Karnataka	411.3	143.8	265.95	190.3	316	145.4	254.1	206.7	1933.55
Kerala	2	0	0	8.5	16.5	0.8	7.5	0	35.3
Madhya Pradesh	29.5	11.4	16.4	130.39	25.1	16.6	46.5	100.5	376.39
Maharashtra	457.3	545.1	485.3	268.15	183	138.9	239.1	416.75	2733.6
Rajasthan	284.8	73.27	111.9	68.95	199.6	350	436.7	545.7	2070.92
Tamil Nadu	2057.3	857.55	577.9	380.67	431.1	602.2	997.4	1083.5	6987.62
West Bengal	1.1	0	0	0	0	0	0	0	1.1
Others	3.2	0	0	0	0	0	0	0	3.2
Total	3635.7	1716.17	1742.05	1663.32	1484.9	1564.6	2349.3	3197.15	17253.54

The output of most machines levels off above the rated speed. Most manufacturers provide graphs, called "power curves," showing how their wind turbine output varies with the wind speed.

4. Cut-out speed—At very high wind speeds, typically between 45 and 80 mph, most wind turbines cease power generation and shut down. The wind speed at which shut down occurs is called the cut-out speed, or sometimes the furling speed. Having a cut-out speed is a safety feature which protects the wind turbine from damage. Shut down may occur in one of several ways. In some machines an automatic brake is activated by a wind speed sensor. Some machines twist or "pitch" the blades to spill the wind. Still others use "spoilers," drag flaps mounted on the blades or the hub which are automatically activated by high rotor rpm's, or mechanically activated by a spring loaded device which turns the machine sideways to the wind stream. Normal wind turbine operation usually resumes when the wind drops back to a safe level.

2.1.2. Solar PV

Solar photovoltaic (SPV) is the process of converting solar radiation (sunlight) into electricity using a device called solar cell. Direct thermal electric conversion methods as applied in solar thermal power generation field mainly includes thermoelectric conversion, thermionic conversion, alkali-metal conversion and magneto hydro dynamic power generation [32]. A solar cell is a semi-conducting device made of silicon or other materials, which, when exposed to sunlight, generates electricity. The magnitude of the electric current generated depends on the intensity of the solar radiation, exposed area of the solar cell, the type of material used in fabricating the solar cell, and ambient temperature. Solar cells are connected in series and parallel combinations to form modules that provide the required power.

The solar PV system shall be designed with either mono/poly crystalline silicon modules or using thin film photovoltaic cells or any other superior technology having higher efficiency.

Three key elements in a solar cell form the basis of their manufacturing technology. The first is the semiconductor, which absorbs light and converts it into electron–hole pairs. The second is the semiconductor junction, which separates the photo-generated carriers (electrons and holes), and the third is the contacts on the front and back of the cell that allow the current to flow to the external circuit. The two main categories of technology are defined by the choice of the semiconductor: either crystalline silicon in a wafer form or thin films of other materials [32].

2.1.2.1. Crystalline solar cells. Most solar cells are made up of a single crystal or multi-crystalline silicon material. Silicon ingots are made by the process of crystal growth, or by casting in specially designed furnaces. The ingots are then sliced into thin wafers. Single crystal wafers are usually of 125×125 mm or larger sizes with 'pseudo-square' shape; multi-crystalline wafers are typically square-shaped with a dimension of 100×100 mm or larger. Using high temperature diffusion furnaces, 'impurities' like boron or phosphorous are introduced into the silicon wafers to form a *p–n* junction. The silicon wafers are thus converted into solar cells. When exposed to sunlight, a current is generated in each cell. Contacts are attached to the top and bottom of each solar cell to enable inter-connections and drawing of the current [32].

2.1.2.2. Thin-film solar cells. Thin-film solar cells are made from amorphous silicon (a-Si), copper indium selenide/cadmium sulphide ($CuInSe_2$/CdS) or cadmium telluride/cadmium sulphide (CdTe/CdS), by using thin-film deposition techniques. These technologies are at various stages of development and have not yet reached the maturity of crystalline silicon. Production of thin-film PV modules is also limited (Fig. 1).

Some of these are specified by the manufacturer, such as the dependence of power output on temperature, known as temperature coefficient [33,34]. The following factors are considered as the key performance indicators:

(1) Radiation at the site.
(2) Losses in PV systems.
(3) Temperature and climatic conditions.
(4) Design parameters of the plant.
(5) Inverter efficiency.
(6) Module degradation due to aging.

India is located in the equatorial sun belt of the earth, thereby receiving abundant radiant energy from the sun. The India Meteorological Department maintains a nationwide network of radiation stations, which measure solar radiation and also the daily duration of sunshine. In most parts of India, clear sunny weather is experienced at the rate of 250 to 300 days a year. Fig. 2 illustrate the western region is having more potential of 6.0 to 6.5 kW h/m^2. All over the year clear sun rays are to getting in the southern region.

The annual global radiation varies from 1600 to 2200 kW h/m^2, which is comparable with the radiation received in the tropical and sub-tropical regions. The equivalent energy potential is about 6000 million GW h of energy per year. The highest annual global radiation is received in Rajasthan and northern Gujarat. For example, assuming the efficiency of PV modules were as low as 10%, this would still be a thousand times greater than the domestic electricity demand projected for 2015 [35].

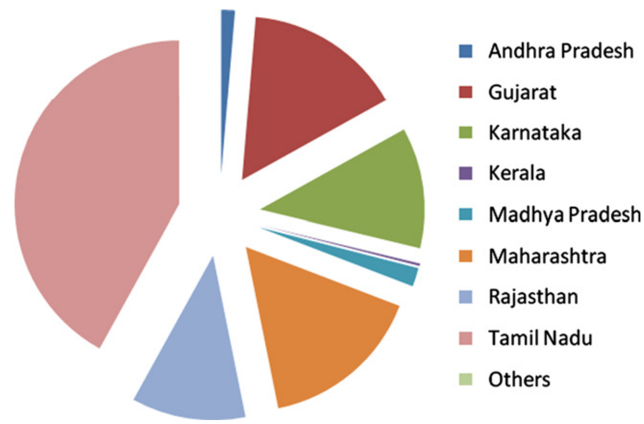

Fig. 1. State wise installed capacity of wind power plant.

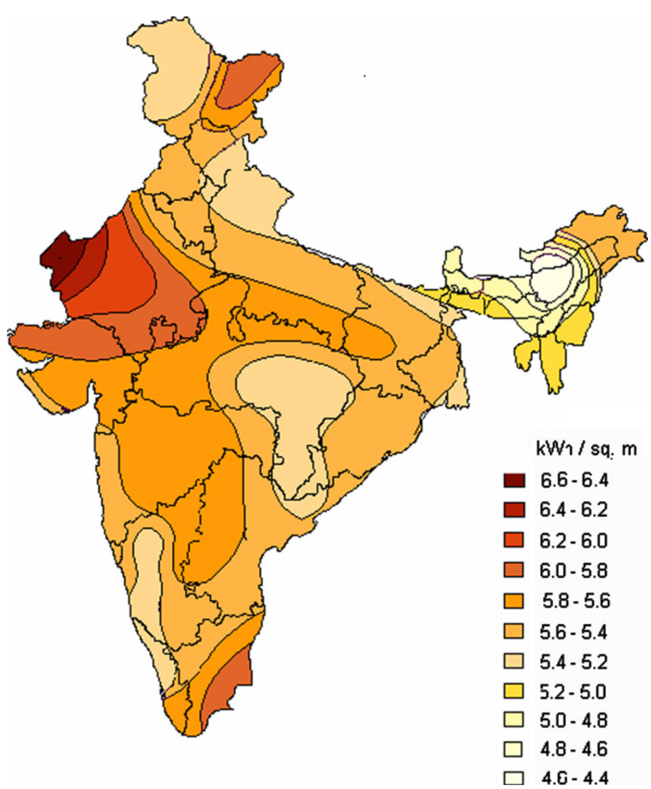

Fig. 2. Solar radiation zones as per The Energy and Research Institute (TERI) based on the India Meteorological Department (IMD) database[30].

Because of its location between the Tropic of Cancer and the Equator, India has an average annual temperature that ranges from 25 to 27.5 °C. This means that India has huge solar potential. PV cells have a low efficiency factor, yet power generation systems using PV materials have the advantage of having no moving parts. The efficiency of solar photovoltaic cells with poly crystal silicon is about 13–17% [35]. High efficiency cells with concentrators are being manufactured, which can operate with low sunlight intensities.

India has SPV power generation potential of 20 MW per sq. km while solar thermal power generation potential of 35 MW/km^2. The grid connected installed capacity at the end of 10th five year national plan was about 3 MW. It is targeted to add 50 MW during the 11th plan [35].

Ministry has approved new projects of 35 MW capacity under the SPV off-grid solar applications, against a target of 32 MW for the year 2010. Around 6 lakh sq.m. of collector area has been installed till January 2011, in addition to installation of different solar air heating and steam generating systems. Thirteen solar steam generating systems (including systems on solar cooling and laundry/process heat applications) and 21 indoor community cookers covering around 4000 m^2 of dish area were sanctioned in 7 States [23].

Jawaharlal Nehru National Solar Mission will be carried out in three phases and aims to do the following: to create a policy frame work deployment of 20,000 MW by 2022; to add 1000 MW of grid solar power by 2013, and another 3000 MW by 2017. This scheme also aims at strengthening indigenous manufacturing capability, and achieving 15 million sq. meters solar thermal collector area by 2017 and 20 million by 2022 [23].

3. Assessment method

LCA is a tool for evaluating the environment impacts of a product or a system throughout its entire life span, usually from raw material extraction to final disposal. When comparing LCA GHG emission results of various energy chains, it is necessary to understand that the electricity generating options may not be true alternatives to each other. For instance, services provided by some energy technologies like irrigation and flood control, reliability of supply, and ancillary services such as voltage control, regulation, operating reserve, load-following and system black-start capability may not be easily provided by all technologies [36]. The LCA can be applied to assess the impact of electricity generation on the environment and will allow producers to make better decisions pertaining to environmental protection [24]. All significant GHG emissions from electricity generation, related to the final product need to be accounted. For electricity this is usually expressed in grams of carbon dioxide equivalent per unit of bus bar electricity (i.e. gCO_2/kW he) [6].

3.1. Type of LCA methodology

LCA methods are generally distinguished between process chain analysis (PCA) and input/output (I/O), although hybrid assessment tools (using elements of both) are also frequently used. PCA is a vertical bottom-up technique that considers emissions of particular industrial processes and operations and includes a limited order of supplying industries and their corresponding emissions, and is therefore an accurate but resource intensive technology [37,38]. PCA strongly relies on GHG content data being available for all relevant materials and processes [39], when in fact complete material inventories are not always available, and manufacturing data for complete systems difficult to estimate—in which case a hybrid approach could use PCA for material assessments and I/O to derive data for certain system operation and maintenance (O&M), manufacturing steps and other processes where complete information is not available [40].

I/O method is a statistical top-down approach, which divides an entire economy into distinct sectors. Based on economic inputs and outputs between the sectors, I/O generates the energy flows and the associated emissions [41]. For example, an established I/O database provides the estimates of the amount of energy required to manufacture classes of products and provides categories of services [40]. However, specific sectors do not exist in I/O table and must be modeled using PCA. LCA based solely on I/O analysis have reportedly produced results that are 30% higher in comparison to results obtained through the PCA method and in the case of nuclear power the deviation can be up to a factor of two [42].

Therefore, it has been frequently suggested to apply a hybrid approach combining LCA and I/O methods, in which the I/O method is used exclusively for assessing processes of secondary

importance, such as energy requirements originating from inputs from upstream supply chains of high order [41,39]. Hybrid models therefore allow the boundaries of the analysis to be broadened by accounting for all processes. This is particularly important where a system comprises of many processes and process steps.

In most of the cases, a combination of PCA and I/O is the most practical approach to LCA [43]. PCA is highly reliable with small truncation errors and will therefore be used whenever practical. However, for many processes, data on energy consumption is not adequately recorded. In these cases, the availability of cost data allows for evaluation using I/O method. I/O method will generally be relied on to evaluate portions of installation, operation, maintenance and decommissioning. Therefore the GHG emission estimates presented here reflect the combination of I/O, PCA and hybrid methodology.

4. Wind energy

Electricity, generated by wind power is regarded as the sustainable electricity. However, in a life cycle perspective also wind turbines consume resources and cause emissions to air, water and soil, primarily during the production and disposal stages but also during its use. In order to determine the precise impacts from electricity produced by a wind turbine, all components needed for the production of electricity based on wind has been included, from the wind turbines to the cables, transformer station and finally the connection to the existing grid. Each of the components in the wind power plant has been considered in the life cycle perspective, i.e. all environmental exchanges related to their production, use and disposal have been included in the calculations.

Concerning the turbines, the most significant environmental impact will arise during manufacturing of the turbines and final disposal of the turbines. On the other hand, the operational stage does not contribute significantly to environmental impacts. Many of the life cycle studies exist for wind turbines for various capacities. The available studies are differing in their scope, but show the dominant influence of the material production on the environmental performance of wind power plants. [44–47]

The turbine system is divided into the following component systems [8]:

- Tower.
- Nacelle.
- Blades (consisting of a three blades and a spinner).
- Foundation for the wind turbine.
- Cables—connecting the individual wind turbines and connecting the wind power plant to the existing grid.

4.1. Material inventory

The main raw material used for manufacturing the Tower, Nacelle and foundation are given in Table 5. The maximum contribution of raw material is in manufacturing of Tower and foundation of tower. The collected data is for the wind turbine, which is 75 m height hub on concrete basement [8].

Table 6, describes the raw materials required for internal cables, transformer and external cables for a 1.65 MW wind turbine. 15 t of the cable are required to connect the wind turbine to existing grit line [8].

4.2. Energy inventory

In Table 7 all energy resources have been included for the entire wind power plant life cycle and related to the production of electricity from the wind power plant. These quantities have been derived from the resource consumption and calculated by means of gross calorific value. As per the site condition, it is estimated that one turbine generates 3029,558 kW h/year. The resource statement of the wind power plant life cycle energy consumption per turbine includes manufacturing, operation, transportation, dismantling and transmission. From that calculation, energy consumption per on shore turbine is 1689,712 kW h/turbine [8]. Table 8.

4.3. Carbon inventory

In the LCI some of the gas is emitting to the atmosphere. From that the contribution of Carbon di oxide is major into polluting the environment. From the LCA carbon emission per kW h power production is 4.64 g [8].

Table 5
Material inventory for the 1.65 MW wind turbine.

S.no	Description	Tonns
1	Tower	136
1.1	Steel	126.1
1.2	Aluminum	2.6
1.3	Electronics	2.2
1.4	Plastics	2
1.5	Copper	1.3
1.6	Oil	1
2	Nacelle	51
2.1	Cast iron	18
2.2	Steel, engineering	13
2.3	Stainless steel	7.8
2.4	Steel	6.3
2.5	Fiberglass	1.8
2.6	Copper	1.6
2.7	Plastics	1
2.8	Aluminum	0.5
2.9	Electronics	0.3
2.10	Oil	0.3
3	Rotor	42.2
3.1	Cast iron	11.3
3.2	Steel	4.2
3.3	Steel, engineering	1.5
3.4	Rest, Epoxy, fibre glass, Birchwood, balsawood, etc	25.2
4	Foundation	832
4.1	Concrete	805
4.2	Steel	27

Table 6
Material inventory for transformer, internal and external cables of 1.65 MW wind turbine.

S. no	Description	Weight (t)
1	Internal cable	0.82
1.1	Aluminium	0.35
1.2	Plastic	0.30
1.3	Copper	0.17
2	Transformer station	0.96
2.1	Steel	0.50
2.2	Copper	0.13
2.3	transformer oil	0.21
2.4	Insulation, paint, wood, porcelain	0.11
3	External cables	14.89
3.1	Plastic	8.35
3.2	Aluminum	5.24
3.3	Copper	1.31

5. Solar energy

A detailed LCI has been made for poly crystalline silicon modules, which includes polycrystalline silicon feedstock purification, crystallization, wafering, cell processing and module assembly with the current status of technology [48]. LCA studies for PV power plants have a long tradition for longer than 15 years. The published studies show a high variation in results and conclusions. The main reasons for different LCI results have been evaluated in the late nineties [49–57]. Here studied the system complexity, and material involved and power consumption and carbon emission in the life cycle stage.

The following assumptions have been made for the study

1. In the case of PV production, the data have been taken from literature [58].
2. The energy production depending on the solar radiation, varies from place to place. Indian atmospheric conditions have been considered for this study.
3. LCI made for the 1.25 m^2 PV module.
4. Considering the balance of system material, the energy consumption of the system has been taken from the average value of literature.

System boundary has been defined as follows

a. The combination of PV module manufacturing, material for BOS and PV energy production have been considered for the system.
b. Mining of raw material is not included in the analysis.
c. All transportation steps are excluded
d. Due to the lack of reliable data, recycling has not been taken in account.

5.1. Material and energy inventory

Material inventory and energy inventory for the poly-Si module are given in Table 9. The basic data has been collected from the literature survey [58].

5.2. Carbon inventory

Table 10 shows the material inventory data of the solar cell modules. These primary data can be used to evaluate carbon emission [58].

5.3. Balance of system

The component has supported to produce the power from the solar light to electricity. The component has contributed to in energy and carbon emission in the LCA. Array support with per square meter of cable and Inverter required power to manufacture is given in Table 11. The corresponding carbon emission also noticed in table [59].

6. Case study—I

6.1. Wind energy

One of the grid interactive wind power project is 25.70 MW which is in and around Udumalpet, Tamil Nadu. The project involves installation, commissioning and operation of 5 numbers of 1.65 MW, 1 number of 0.95 MW and 22 numbers of 0.75 MW totally contributing 25.7 MW of power to the regional grid. It came to operation on 2004–2005. The details of the capacity installed in various locations are listed in Table 12. The detailed study is carried out for one of the 1.65 MW wind turbine.

Most wind turbines start generating electricity at wind speeds of around 3–4 m/s (m/s), (8 mph); generate maximum 'rated' power at around 15 m/s (30 mph); and shut down to prevent storm damage at 25 m/s or above (50 mph) [24].

The average wind speed of Tamil Nadu is 6–7 m/s. The capacity factor in the Tamil Nadu region is 20.96% [24]. Before calculating the production of power, life time of the turbine must be calculated. The general life time of wind power plant turbine is 20 years. The wind power production can be calculated using Eq. (1). Consider the Udumalpet wind power plant; the power production in the life period is 930.83 GW h (Table 13).

$$\text{Wind power production (MW)} = \text{Installed capacity (MW)} \times \text{Capacity factor} \quad (1)$$

Table 8
Carbon and other gas emissions per kW h power production.

S. no	Emissions (g/kW h produced)	Onshore
1	CO_2	4.64
2	Sulpher dioxide	0.0218
3	Nitrogen oxides	0.0177
4	Carbon monoxide	0.00813
5	Organic emission to air (group VOC)	0.0147

Table 7
Energy consumption per kW h power production.

Non- renewable energy fuels	kG	MJ/kg	MJ
Crude oil (resource)	0.000714	45.7	0.0326
Hard coal (resource)	0.00129	25.2	0.0325
Lignite	0.000229	9.58	0.00219
Natural gas	0.000522	50.7	0.0265
Uranium	9.98E−09	629000	0.00627
Renewable energy fuels			
Biomass	0.000131	22.5	0.00294
Wind power	–	–	0.000121
Hydro	–	–	0.00509
Solar	–	–	0.0000987
Geothermic	–	–	0.0000309
Total (MJ/kW h produced)	–	–	0.108
Total (kW h/kW h produced)	–	–	0.0301
Total (kW h/turbine) in the life time	–	–	1689712

Table 9
Material and energy inventory for the poly crystalline solar cell.

S. no	Process	Energy consumption (kW h/module)
1	High purity silicon production	128.96
2	m-Si wafer production	21.06
3	Solar cell production	26.55
4	m-Si module assembly	20.59
5	Aluminum production	98.1
6	Glass production	33.11
7	EVA production	12.263
8	Copper production	0.61
9	Tedlar production	5.15
Total Energy consumption		346.39

Table 10
Carbon emission per module manufacturing of solar cell.

S. no	Process	kg CO_2 emission per module
1	m-Si module production	5.09
2	Aluminum production	62.25
3	Glass production	1.85
4	EVA production	0.45
5	Copper production	0.65
6	Tedlar production	2.30
Total CO_2 emission		71.49

Table 11
Energy and carbon emission for the BOS.

Material	Energy input	CO_2-eq emission
Array support + cabling	2.778 kWp/m^2	6.1 kg/m^2
Inverter	1930 MJp/kWp	125 kg/kWp

6.1.1. Energy pay back period

The energy balance is an assessment of the relation between the energy consumption of the product and the energy production throughout the life time.

The energy balance has been calculated as the relation between the turbine's energy consumption for manufacturing, operation, transport, dismantling, disposal and the expected average energy production.

The energy consumed for the 1.65 MW wind power plant is 3392 MW per turbine. This is nothing but the energy consumed in the life cycle per turbine. The power production for the 1.65 MW wind turbine is 3029.56 MW per turbine in a year. The energy payback period for the above capacity wind turbine is 1.12 year (Table 14). The energy payback period calculated using Eq. (2).

$$\text{Energy payback period} = \frac{\text{Energy consumed pertrubin (MW)}}{\text{Energy produced by turbineperyear (MW)}} \quad (2)$$

6.1.2. Carbon intensity and carbon pay back period

Carbon intensity is nothing but, the carbon emission associated with manufacturing, operation and decommissioning of the wind turbine per unit of electricity production over the life time. The simplified equation is given below.

$$CO_2\text{ intensity} = \frac{\text{Lifecycle } CO_2 \text{ emission (gram of } CO_2)}{\text{Lifetime power generation (kW)}} \quad (3)$$

Carbon pay back period is nothing but, a measure of how long a CO_2 mitigating process needs to run to compensate the CO_2 emitted to the atmosphere during a life cycle stage. 1.65 MW wind turbine is required to run 50 days to recover the carbon emitted in the life cycle stage (Table 15).

$$\text{CPBP} = \frac{\text{Life cycle } CO_2 \text{ emission}}{\text{Gross } CO_2 \text{ emission avoidedd per year}} \times 365 \quad (4)$$

Table 12
Installed capacities in various locations in Udumalpet.

S. no	Capacity (MW)	Quantity	Total capacity (MW)	Year of commission	Location
1	0.75	12	9	2004–2005	Kongalnagaram
2	0.75	2	1.5	2004	Gomangalam
3	0.75	2	1.5	2004–2005	Dasarpatti
4	0.75	6	4.5	2004–2005	Andhiyur
5	0.95	1	0.95	2005	Edayarpalayam
6	1.65	1	1.65	2004–2005	Kongalnagaram
7	1.65	3	4.95	2004–2005	Andhiyur
8	1.65	1	1.65	2004–2005	Udumalpet
Total		28	25.7	–	–

Table 13
Life time production of the 25.7 MW project.

Installed capacity	Capacity factor	Production (MW/h)	Production per year (GW h/ year)	No. of unit	Life time	Life production (GW h)
1.65	20.96	0.34584	2.99	5	20	298.81
0.95	20.96	0.19912	1.72	1	20	34.41
0.75	20.96	0.1572	1.36	22	20	597.61
Total						930.83

Table 14
EPBP for the 1.65 MW wind turbine.

Wind turbine capacity (MW)	Efficiency of the system	Life time (Year)	Power generation per year (MW)	Life cycle energy consumption (MW)	EPBP (Year)
1.65	20.96%	20	3029.56	3392	1.12

7. Case study—II

7.1. Solar PV

For this study we have taken the grid interactive roof top solar PV power plant at Sewa Bhawan, R.K. Puram, New Delhi. The details of the site are given in Table 16.

7.1.1. Energy pay back period for the 25 kW power plant

In the Sewa Bhawan site, 150 nos of grid connected poly crystalline module is available and each module is having nearly 113 w capacity. As per the technical data of the site condition and the PV module capacity, the total power generated in the roof top system is 42 MW per year. The total power consumption in the manufacturing module is 66.96 MW (Tables 17 and 18).

$$\text{EPBP (year)} = \frac{\text{Total primary power consumption for manufacturing PV module (kW)}}{\text{Annual primary power generation of PV module (kW/year)}} \quad (5)$$

Using Eq. (4) the energy payback period has been calculated. The total power consumption in manufacturing of PV module is recovered from the 16 months of the operation of the plant (Table 17).

Table 15
Carbon Pay Back Period for the 1.65 MW wind turbine.

Life time power production (MW)	CO_2 intensity (kg/MW)	Carbon intensity of coal based power plant (kg/MW)	Carbon reduction (kg/MW)	CO_2 emission in life time (kg)	Gross CO_2 reduction (kg/year)	CPBP (Days)
60,591.17	6.50	941	934.50	393,842.59	2831,122.32	50.78

Table 16
Technical details of the Sewa Bhawan roof top solar PV plant.

1	Location	
I	State	NCT Delhi
Ii	Locality	West Block are, R.K.Puram
Iii	Name of building	Sewa Bhawan
Iv	Latitude	77°12′
V	Longitude	28°32′
2	Area for SPV plant	
I	Length	25.5 m
Ii	Width	13.0 m
Iii	Location	Terrace of North Wing of Sewa Bhawan (Eastern side of terrace)
3	SPV power plant	
I	Output	25 kWp
Ii	No. of modules	150
Iii	No. of modules in series	5
Iv	No. of parallel combination	30
V	DC BUS	1 No.
4	Technical details of a SPV module	
A	PV Module type	Poly crystalline
B	Physical Dimensions	
I	Length with frame	1580 mm
Ii	Width with frame	795 mm
Iii	Thickness	40 mm
C	Electrical parameter	
I	Maximum power rating	170 kWp
Ii	Rated current	5A
Iii	Rated voltage	34 V
Iv	Short circuit current	6A
V	Open circuit voltage	42.8 V
5	Mounting arrangement	
I	Mounting	Fixed type
Ii	Surface azimuth angle of PV module	180°
Iii	Tilt angle (slope) of PV module	23.32°
6	Inverter/power conditioning unit (PCU)	
I	Number of units	1
Ii	Rated capacity	27 kWp
Iii	Input voltage range	170 V ($_{Max.}$)
Iv	Output voltage	440 V AC
V	Frequency	50 Hz
Vi	Efficiency	94%
7	Grid connection details	
I	Electrical parameters for interconnection	440 V, 3 Ph, 50 Hz
8	Annual energy generation	
I	Annual energy	42 MW
9	Cost estimate	
I	Estimated cost (Rs. Lakh)	42.5
Ii	Cost per kW (Rs. Lakh	1.7
10	Cost of energy generation	
I	Levelised tariff (Rs/kW h)	18.45
Ii	Cost of generation (Rs/kW h)	10.54
11	Construction time	5 months

The following assumptions has been made for the below calculation

Assumption	
Efficiency of the PV module	– 15%
Losses in DC circuit	– 3%
Converter Efficiency	– 92%
Losses in AC circuit	– 3%
Life time	– 25 years

Table 17
Energy pay back period for the 25 kW Solar PV power plant.

Capacity (kW)	Avg. radiation (kW h/m^2/d)	Power generation MW per year	Total Module	Total Power consumption (MW/Plant)	EPBP (year)
25	5.31	41.67	150	66.96	1.6

7.1.2. *Carbon intensity*

The carbon intensity is nothing but, the carbon emission associated with manufacturing, operation and decommissioning of the solar cell per unit of electricity production over the life time. CO_2intensity has been calculated based on Eq. (3)

From the literature of the LCA of the poly crystalline PV module the carbon emission has been calculated as 71.49 kg of CO_2 per module. The life time power generation of the Sewa Bhawan site is 1041 MW. From that, the carbon emission is 14.65 g of CO_2 per kW h power production (Table 18).

7.1.3. *Carbon pay back period*

Carbon emission reduction in the solar in Sewa Bhawan, roof top solar power plant is given in Table 19. Based on the CDM calculation data, the coal based power plant is emitting 941 kg of CO_2 per MW of power production. But the Poly crystalline PV module emits 14.65 kg for the MW of power production, which has been generated in the manufacturing stage of the PV module. The carbon reduction of the 25 kW roof top power plant is 930 kg power MW of power production.

This is a measure of how long a CO_2 mitigating process needs to run to compensate the CO_2 to the atmosphere during a life cycle stage. Using Eq. (4) the carbon payback period has been calculated for the 25 kW poly crystalline roof top system. The carbon has been recovered in 143 days of operation of the solar PV power plant.

8. Comparison of case study

In Table 20 two renewable energy technologies are compared with respect to the environmental concern. Both the technologies reduce the carbon compared with the coal based power plant. But the wind energy technology reduces more carbon than the solar PV system. Solar energy takes 5 months more than the wind energy to produce the energy which has consumed in the life cycle. Solar energy takes three times more than the wind energy to mitigate the carbon which is emitted in the life cycle stage.

9. Conclusion

The present paper gives the result of LCA of wind turbine and Roof Top poly crystalline PV module which is operating at Udumalpet, Tamilnadu and Sewa Bhavan New Delhi, respectively. Carbon intensity of the solar power plant is high compared with

Table 18
Carbon emission per unit of power generation.

kg CO_2 emission per module	Total module	kg CO_2 emission for PV	kg of CO_2 emission for BOS	Total kg of CO_2 emission	Total power production per year	Life time production MW	CO_2 intensity kg/MW
71.49	150	10,723.5	4534	15,257.5	41.67	1041.76	14.65

Table 19
Carbon pay back period for the 25 kW grid connected roof top system.

kg CO_2 emission per MW	Carbon emission of coal based power plant kg CO_2/MW	Carbon reduction kg/MW	Life cycle CO_2 emission (kg)	kg of CO_2 reduction per year	CPBP (Days)
14.65	941	926.35	15,257.5	38,782.53	143.60

Table 20
Comparison of 1.65 MW wind turbine and 25 kW Grid connected roof top system.

Technology	Capacity	Power production (MW/Year)	Carbon intensity (gCO_2/kW)	Life cycle energy consumption (MW)	Life cycle CO_2 emission (kg)	Carbon reduction kg/MW	EPBP (year)	CPBP (days)
Wind	1.65 MW	3029.56	6.5	3392	393,842.59	934.5	1.12	50.78
Solar	25 kW	41.67	14.65	66.96	15,257.5	926.35	1.6	143.60

the wind power plant. Carbon emission and the manufacturing stage of PV module and BOS make the more contribution. With increasing the productivity of the PV module will reduce the carbon intensity in the future. Energy pay back period is calculated for both at the systems, from that solar PV system needs to run three month more to equal the wind energy. The loss of energy in the DC to AC conversion process is high in the solar PV system. That makes difference in the EPBP.

Carbon emission per unit power production is very low compared with the coal based power plant. From that data, it is arrived that CPBP for the wind and solar PV power plant. By comparing these data, solar PV system is three times less than the wind energy system.

From the above study, environmental impacts are more for solar PV system compared with the Wind energy system. The environmental impacts of solar PV system can be reduced by better development in the manufacturing process, controlling the energy loss in the circuit and increasing the efficiency of the PV cell and convertor.

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